Automated Reasoning and Autonomy in NASA Missions

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Outline

- **Overview of Intelligent Systems Project/Automated Reasoning Element**
  - **Goal/Objective**
  - **Motivation**
  - **Expected Impact**
  - **Strategic Plan**
- Automated Reasoning: Technology Areas
  - Intelligent Sensing and Reflexive Behavior
  - Planning and Execution
  - Model-based Fault Protection
  - Distributed Autonomy and Architectures
  - Verification and Validation of Autonomy
- Examples of Research Projects
  - *Descent Image Motion Estimation Subsystem for MER*
  - *NeuroControl for Shuttle Docking*
  - *MAPGEN for MER*
  - *Benchmarking Tools in Verification*
  - *Single Cycle instrument Placement*
  - *Autonomous Science Inference*

Goal and Objective

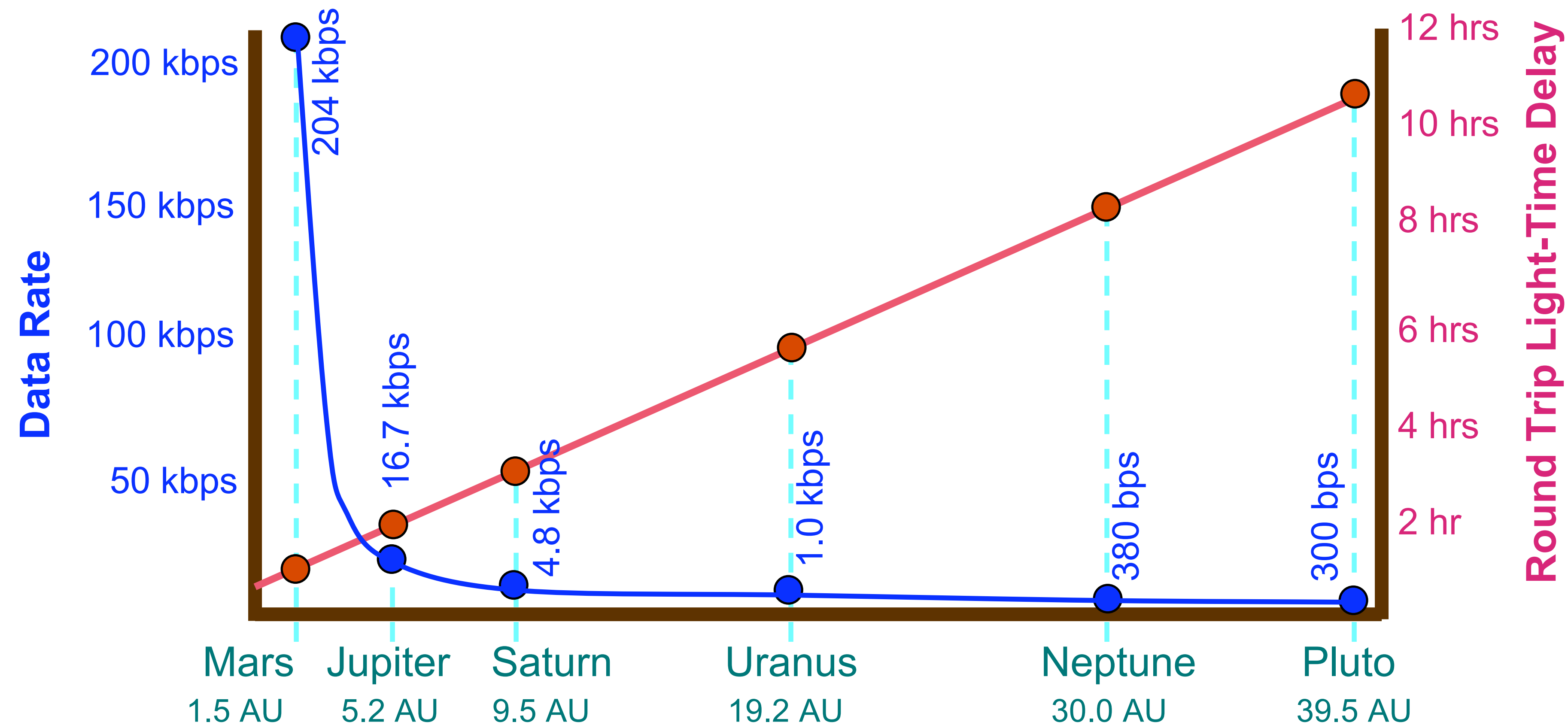
- Increase the overall level of intelligence exhibited by spacecraft and other complex systems required to support NASA's missions.
- Support strategic research in automated reasoning to enable the creation of integrated software and hardware systems that reliably make and execute decisions which traditionally have either been made entirely by, or required intervention by, humans.

Motivation

- Future space missions will need to perform complex operations in order to meet minimum mission science objectives within reasonable costs.
  - Precision landing on a hostile environment
  - Accurate instrument placement for sampling or imaging.
  - Remote exploration without earth contact for a week or longer.
- Attempting these operations with ground controllers
  - Introduces long latencies
  - Imposes heavy demands on operations team
  - Is less responsive to the dynamic and uncertain situations these missions will face.
- Automated reasoning technology will help NASA missions by
  - Increasing the amount of science that can be achieved
  - Ensuring safety of spacecraft and surface explorers in hostile and unknown environments
  - Enabling more robust mission operations

Time Delay/Data Rate for Remote Communication

Effect of distance on data rate for X-band RF communication with 5 watts transmitted power from a 2-meter spacecraft antenna into a 70-meter ground antenna



At orbit of Pluto it will take ~10 hours to send a command from Earth and receive acknowledgement!

Complexity Comparisons for Mars Missions

	Sojourner	MER	MSL
Mission Duration	30 days	90 days	1,000 days
Total Traverse	100 m	600 - 1000m	3,000 - 69,000 m
Meters / sol	3 - 10 m	100 m	230 - 450 m
Science Mission	• APXS	• 5 instruments • rock-abrader	• 7 instruments • sub-surface science package (drill, radar) • in-situ sample “lab”

Mission complexity is increasing

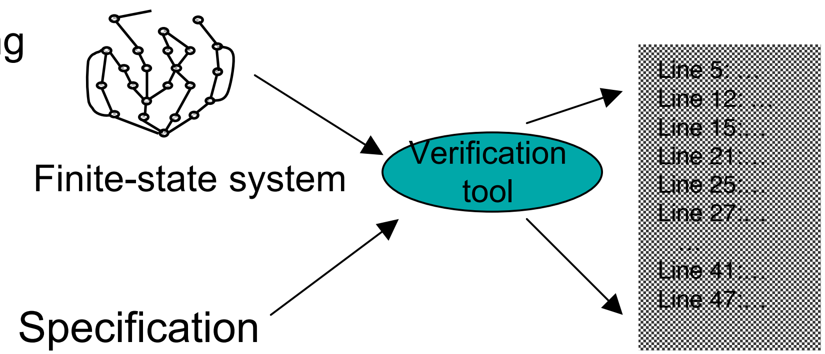
Time spent waiting for instructions must decrease
(longer traverses, more science/sol)

Demands on operations teams are increasing
(fast uplink/downlink turnaround, complex missions & science decisions, over longer missions)

Impacts of Autonomy

- **Unmanned, deep space exploration using intelligent spacecraft, rovers, and mission operations tools.**
  - A new generation of automated reasoning capable of operating in dynamic and hazardous environments while maximizing science return to Earth
    Impact: Increase in science returned from a mission

- **Software tools which allow the automated generation and testing of autonomy code for flight software**
  - Requires the development of formal methods and model-based reasoning techniques to enable automated generation and testing of autonomy generation and testing of autonomy software
    Impact: Reduction in ground operations staff per mission



Strategic Plan and Metrics

- Support basic research in technology for enabling autonomy in NASA missions
- Demonstrate technologies that support the need to significantly increase the level of autonomy within NASA's future missions
- Support mission infusion efforts in autonomy
- System Performance Metric: increased degree of autonomy (ratio of machine decisions to human decisions performed during a mission)

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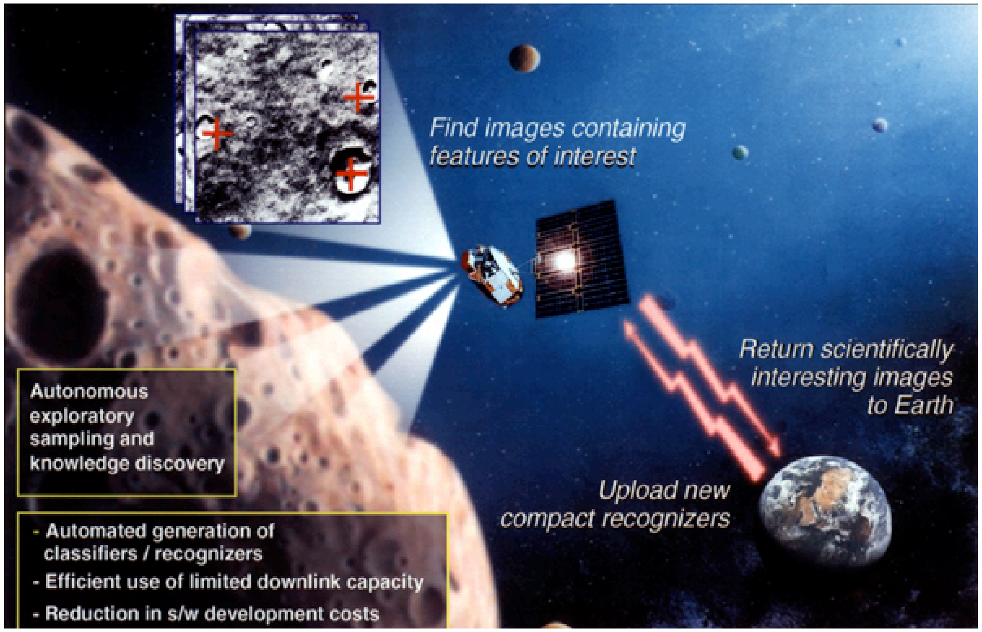
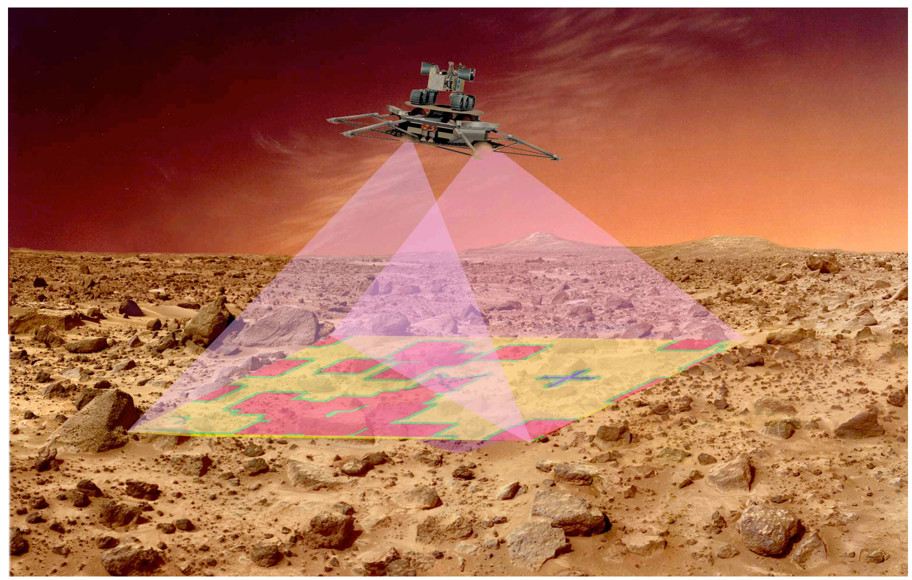
Intelligent Sensing and Reflexive Behavior



- Goal: develop systems with situational awareness
  - Respond to external threats to system
  - Adapt to changes in environment and system
- Emphasis on reactivity, not deliberation.

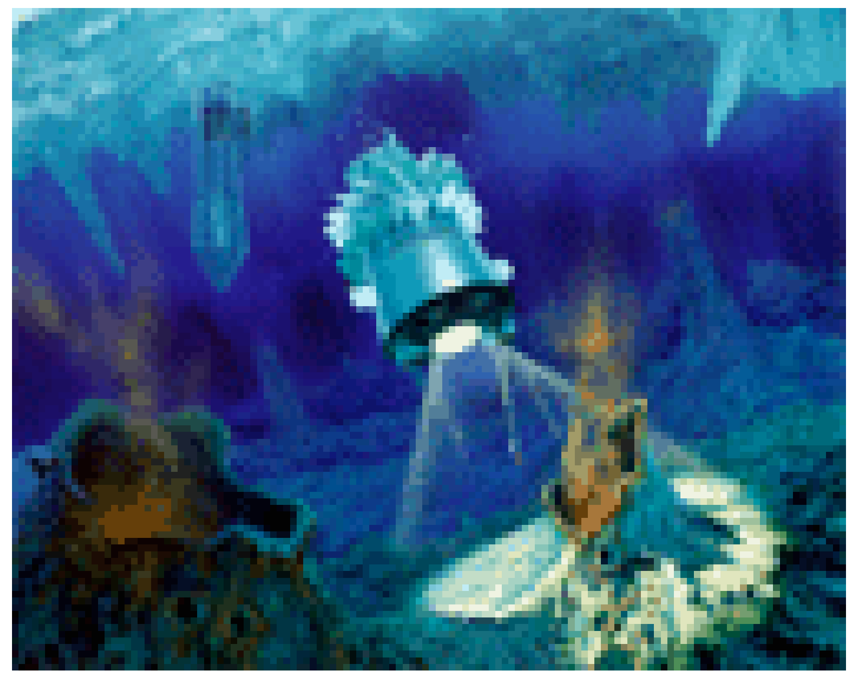
Research challenge:

- Develop computational approaches to reflexive behavior that improve the ability of autonomous systems to maintain their health while detecting scientifically important objects, events, and situations in its environment.



Planning and Execution

- Develop automated planning systems for decomposing high level goals into sequences of activities that satisfy temporal, resource, and other constraints.
- Develop systems for robust execution of command sequences while monitoring and responding to system failures



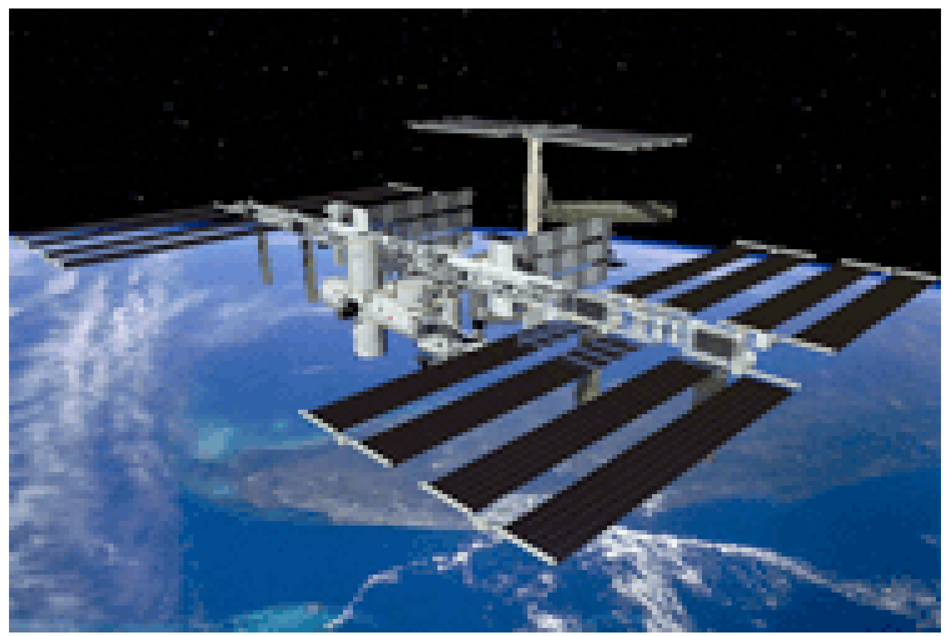
Research Challenge:

- Large-scale, concurrent planning under uncertainty involving continuous quantities such as time and resources.

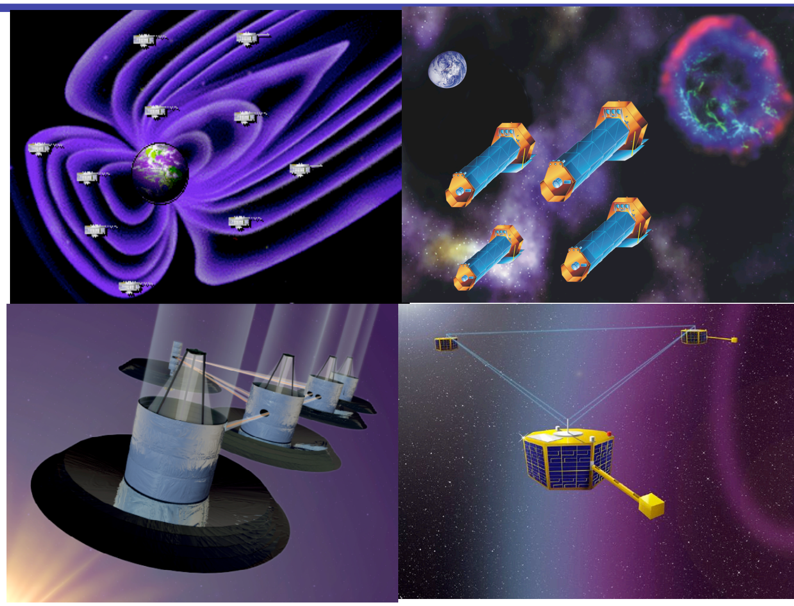
Model-based Fault Protection

Research Challenge:
Automated diagnosis for discrete and continuous failures, for discriminating between component failure and environmental influences, and for folding model-based fault management into an autonomous executive control loop.

- **Develop methods for detecting, diagnosing and reacting to mission events through the use of explicit models of hardware and software components.**
- **Model-based specification of system behavior at the component level, rather than the system level.**



Distributed Autonomy and Architectures

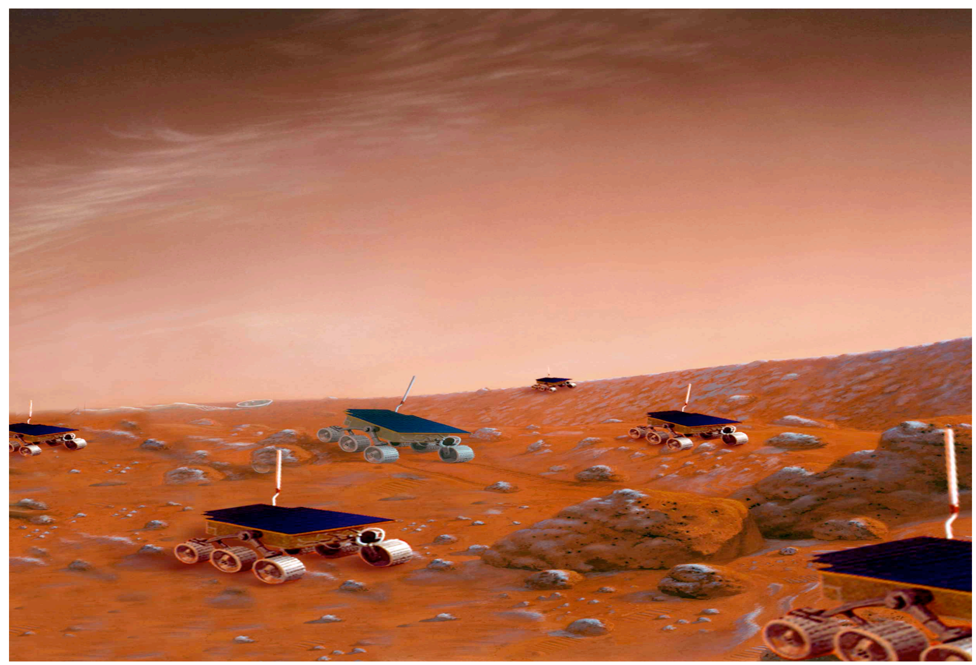


•**Develop capabilities that allow autonomous systems to coordinate activities in order to achieve a common goal.**

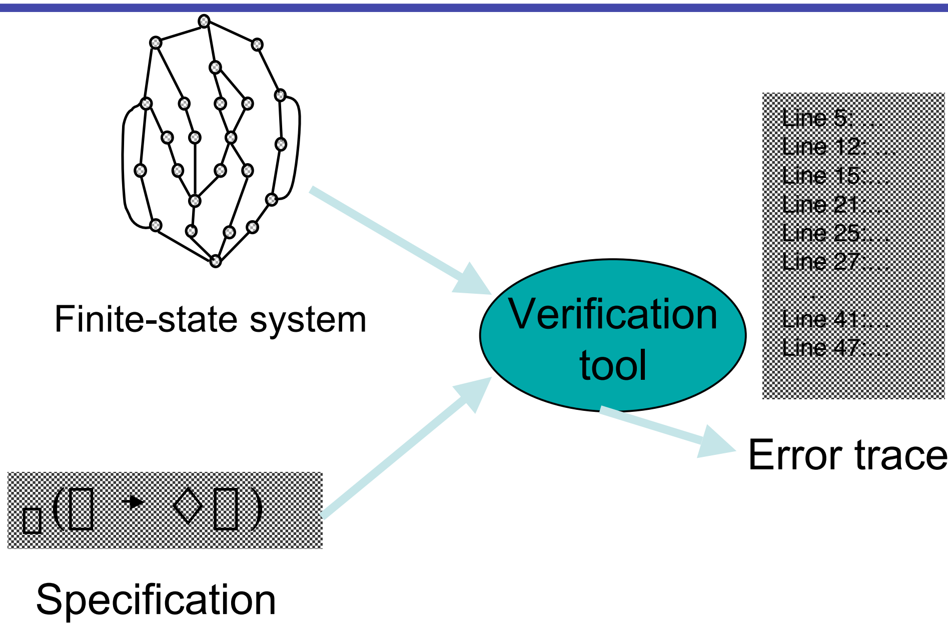
•**Develop techniques for controlling and coordinating multiple-asset missions.**

Research Challenges

- Planning and scheduling to enable coordinated operations
- Low-bandwidth approaches to onboard coordination.
- Ad hoc networking of existing satellites
- Collective fault detection, isolation and recovery.



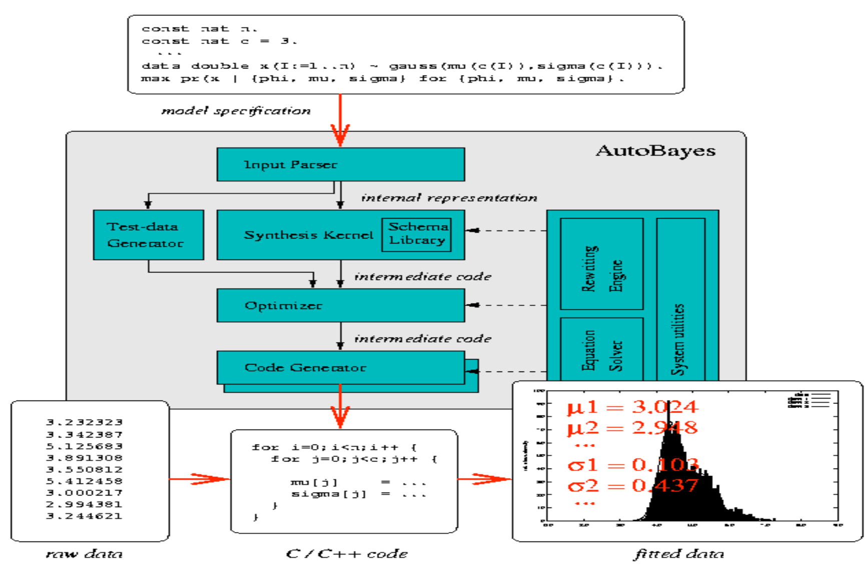
Automated Software Engineering for Autonomy



- Build high-assurance software generators that target autonomy capabilities
- Create/adopt standards for software Integration of autonomy components
- Develop verification methods at different levels of granularity
- Methods for verifying software that adapts and learns

Research Challenge:

Addressing the complexity in verifying autonomy systems that operate in rich and uncertain environments, and that must adhere to internal correctness constraints involving communication among components, control flow, and resource utilization.



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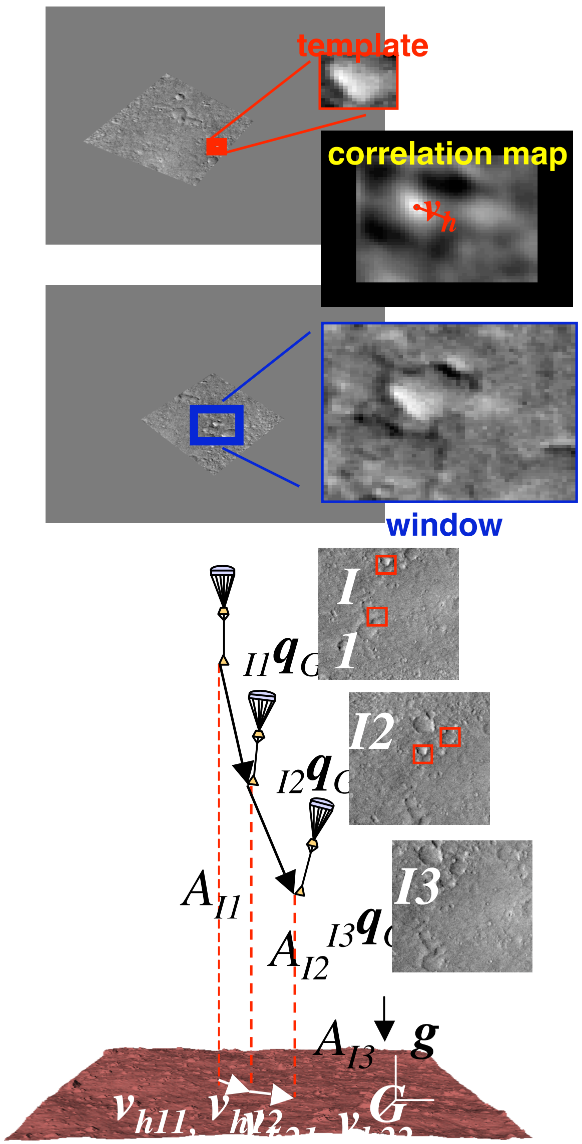
Intelligent Sensing and Reflexive Behavior

Descent Image Motion Estimation Subsystem for MER

APPROACH



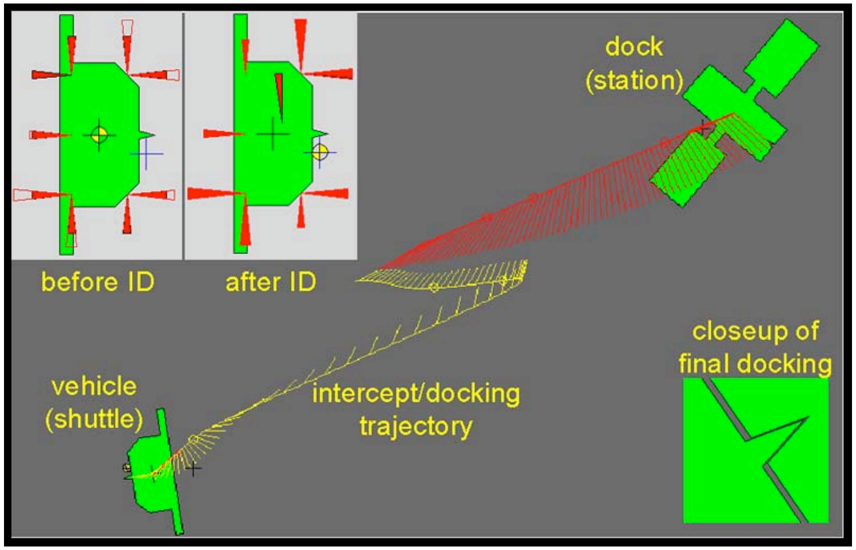
Problem: Steady state winds during descent could impart a surface relative horizontal velocity to the Mars Exploration Rovers (MER) landing system, threatening lander safety.

Solution: estimate the horizontal velocity of the lander from images taken of the surface during terminal descent.

Approach: DIMES computes horizontal velocity, checks the answer for validity and passes a horizontal velocity correction to the Transverse Impulse Rocket Subsystem (TIRS). TIRS uses the horizontal velocity correction along with measurements of attitude to compute a TIRS rocket firing solution that reduces both RAD rocket and steady state wind induced horizontal velocity.

Intelligent Fault Management

NeuroControl for Shuttle Docking



PROBLEM: Docking a spacecraft under manual joystick control can be risky, and is highly dependent on the skill of the pilot. Docking to a spinning target is generally too dangerous to attempt.

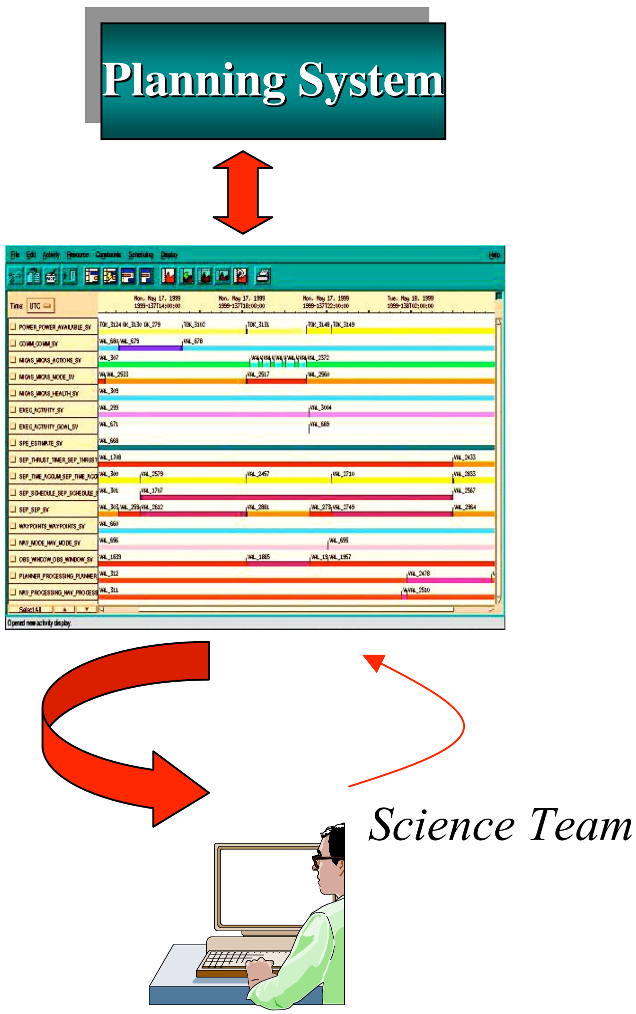
OBJECTIVES: Adaptive, intelligent, fault-tolerant controllers that can learn (in real time) changes in vehicle mass properties, thruster strengths and failures, leak thrusts, and other disturbances. This will enable safer, more accurate, and more fuel-efficient control of spacecraft navigation and docking, including safe docking to a moving target.

APPROACH: Adaptive neurocontrol technologies will be used to learn a model of the spacecraft from its operating behavior. Optimal control information communicated to the astronaut through a combination of visual and force-feedback signals. Performance of semi-automated and fully automated control modes will also be tested, allowing "scalable autonomy" as needed by future missions.

PROJECT STATUS: Experiments on ISS under MIT/SPHERES project focus on testing technologies on real-time spacecraft mass property identification using motion sensor information. In preparation, preliminary engineering testing of technologies were conducted using the SPHERES in KC-135 0g flights in Feb 2003.

Planning and Execution

MAPGEN for MER



Science is the primary driver of MER and making best use of the rover scientific instruments, within the available resources, is a crucial aspect of the mission.

To address this criticality, the MER project has selected MAPGEN (Mixed-Initiative Activity Plan GENerator) as an activity planning tool.

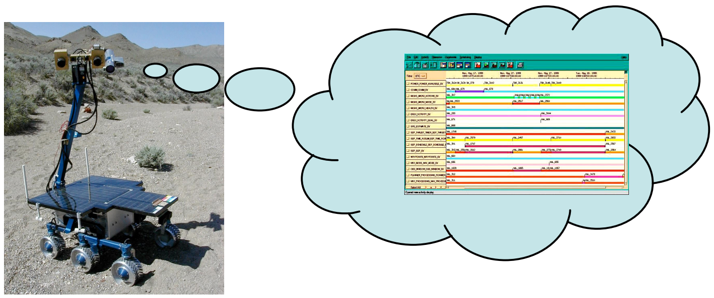
MAPGEN has the following capabilities:

- Automatically generates plans and schedules for science and engineering activities.
- Hypothesis testing (using what-if analysis on various scenarios).
- Plan Editing.
- Resource computation and analysis.
- Constraint enforcement and maintenance.

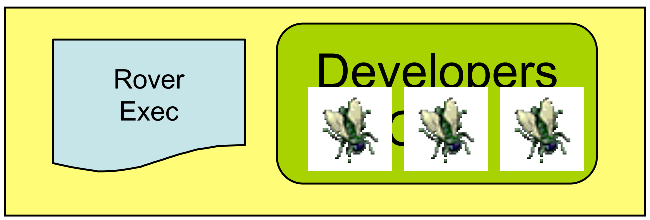
MAPGEN combines two existing systems, each with a strong heritage: APGEN the Activity Planning tool from the Jet Propulsion Laboratory and the Europa Planning/Scheduling system from NASA Ames Research Center.

Verification for Autonomy

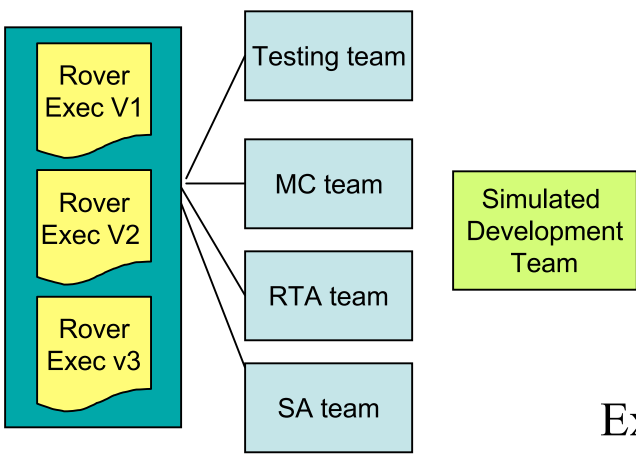
Benchmarking Tools in Verification



Challenge: benchmark the state-of the art in advanced V&V tools as applied to autonomy software.



Experimental input: the code for an autonomous rover executive and the log of software defects during its development.



Experimental setup: simulated a development team producing 3 successive versions of the rover software. Experimental subjects were 4 independent V&V teams using individual advanced tools or baseline testing-only group. Simulated development team fixed bugs as V&V teams found defects.

Experimental outcome: 400 hours of data acquired on use of advanced V&V tools. Effectiveness on autonomy software was demonstrated.

Integrated Autonomy Demonstration

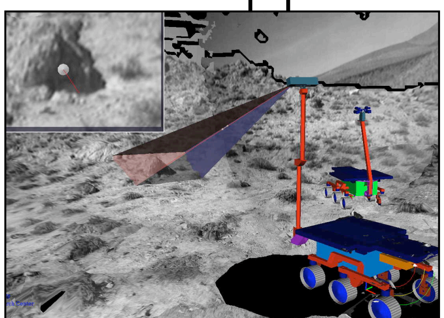
Single Cycle instrument Placement

Robot at site

- Acquire 360° image panorama
- Downlink data

Data Analysis/ target generation

- Build or update 3D model
- Designate target(s)
- Prioritize targets



Rover Planning

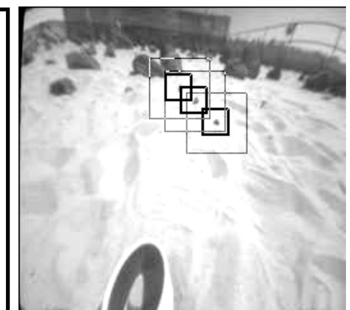
- Contingencies
- Flexible times
- Concurrent activities
- Verify sequence
- Uplink sequence

Remote spectra of targets

- **Onboard analysis** of spectra to prioritize targets

Approach highest priority target and deploy microscopic imager on it.

- **Robust execution** of contingent, concurrent, flexible time sequence
- Monitor resource consumption
- Monitor for present and future hazards
    - Obstacles
    - Forecast low battery condition
- Verify placement and instrument data



Downlink data + diagnostic images

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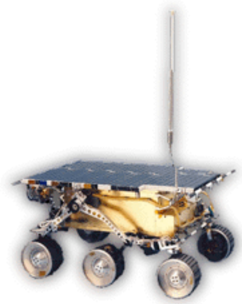
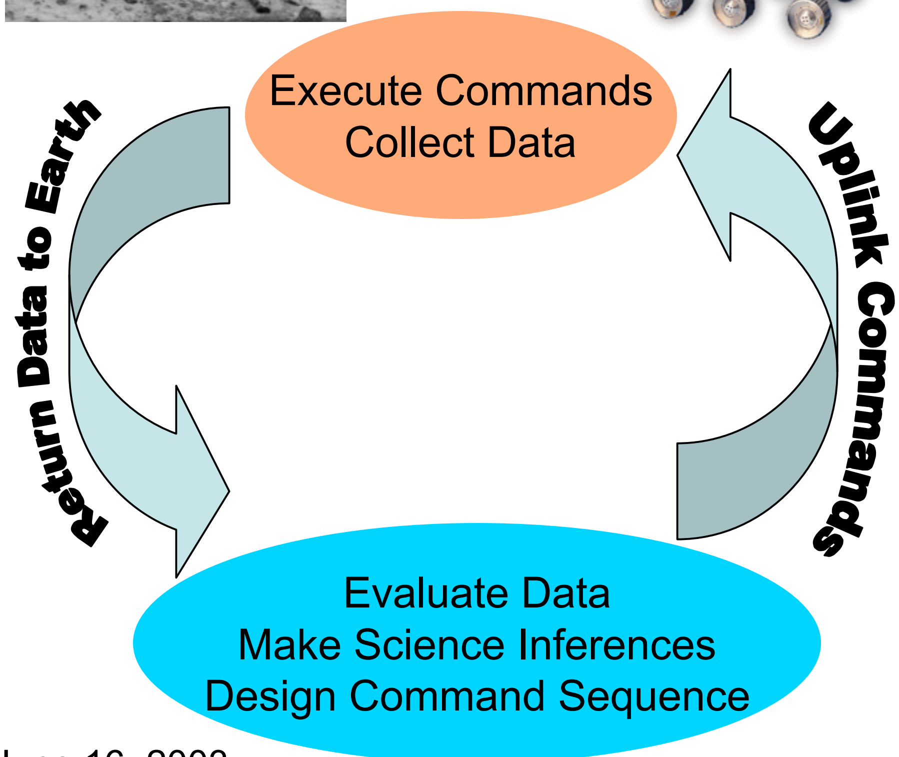
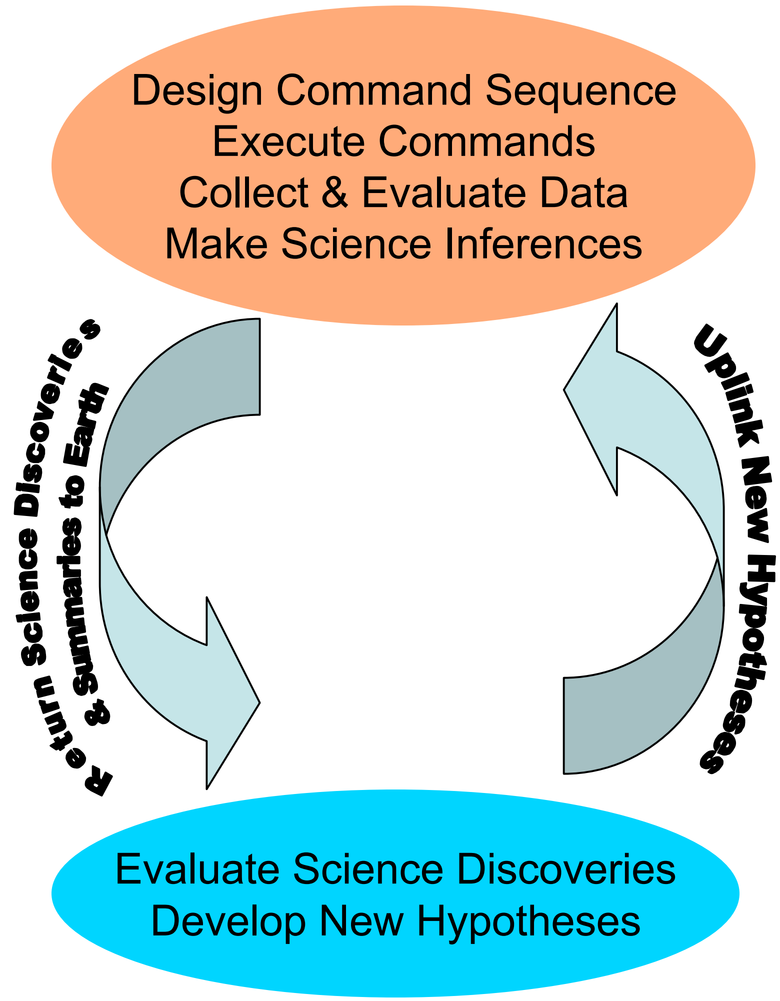
Integrated Autonomy Demonstration
Autonomous Science Inference

Historical Spacecraft Mission





Science-Enabled Spacecraft Mission



Integrated Autonomy Demonstration

Autonomous Science Inference

Objective: Enable increasing levels of science decisions to be made on-board robotic explorers

- **Assure quality science data collection**
  - instrument failure detection & recovery
    - correct target sampled?
    - evaluate sensor operational characteristics
  - assess data quality
    - longer integration required
    - reposition sensor or rover
- **Evaluate data for science content**
  - reduce science data volume
    - data correlation
    - data fusion
  - science used for transmission prioritization
    - evidence for carbonates
    - evidence of layers
- **Science inference on-board directs future activity**
  - recognize unique observations
    - carbonates
    - clays
    - fossils
  - summarize science content of sensor readings

Summary

- AR objective: Support strategic research to enable the creation of systems that reliably make and execute decisions traditionally made by humans.
- Autonomy leads to
  - Increased mission assurance: Ability to respond to a wider range of environmental and system health conditions.
  - Improved performance: Increased science return and more efficient operations due to the systems ability to respond to opportunities.
  - Decreased cost: Reduction in mission ops cost and potential decrease in mission development costs.
- AR strategy:
  - Build component autonomy technology
    - Based on 5 key technology areas
  - Demonstrate integrated systems
  - Mission infusion